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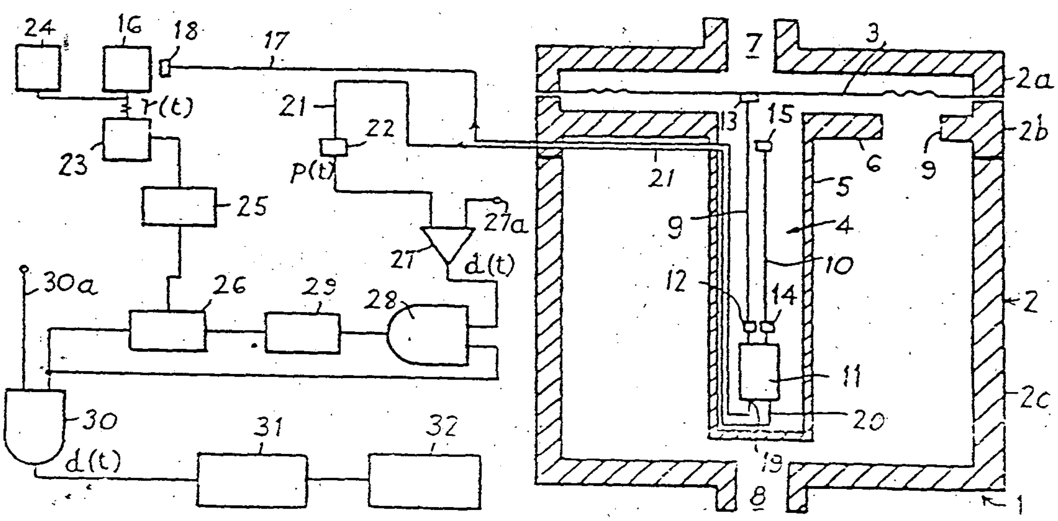

(57) Abstract

Optical pressure sensing apparatus comprises an optical fibre interferometer (4) arranged to sense the movement of a pressure responsive element (3) and produce an interference signal at its output (20) which can be monitored and processed to measure changes in the pressure applied to the pressure responsive element. The interferometer comprises a signal arm (9) coupled to the pressure responsive element (3) and a fixed reference arm (10). A light source (16) supplies light to the input (19) of the interferometer via an optical fibre (17) and monitoring and processing electronics (22-32) connected to the output (20) determine the optical phase shift between the light beams propagated in the signal and reference arms (9, 10) and produce a pressure reading.

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OPTICAL PRESSURE SENSING APPARATUS

The present invention relates to optical pressure sensing apparatus and, more particularly, to such apparatus utilising the principles of an optical fibre interferometer for sensing small pressure induced displacements of a pressure responsive element.

The principles of interferometery are well known and their application to the sensitive measurement of displacements is also established. However, the necessity of having to use large and heavy optical components and light sources in precise alignment has limited their practical application.

An object of the present invention is to provide a pressure sensing apparatus which employs the high sensitivity of an optical fibre interferometer to achieve both improved sensitivity to small pressure changes and measurement over a large dynamic range.

To this end, the invention consists in an optical pressure sensing apparatus characterised by an optical fibre interferometer device arranged to sense the movement of a resilient pressure responsive element, whereby an interference signal produced at an output of the interferometer device is responsive to change in the pressure applied to the pressure responsive element. The latter may be any type of resilient element employed for pressure sensing purposes, for example, a diaphragm, capsule or one of a selection of tubes of different geometries, and an element of appropriate mechanical

properties is selected depending upon the particular application.

Preferably, the interferometer device comprises individual optical fibre signal and reference arms, the signal arm being mechanically or optically coupled to the pressure responsive element so that the length of the optical path defined by the signal arm changes relatively to that of the reference arm in response to movement of the pressure responsive element. The signal and reference arms have equal responses to physical pertubations, such as, temperature changes, other than the desired pressure measurand and these cancel one another by the process of common mode rejection. Such apparatus therefore shows negligible cross sensitivity. Moreover, once calibrated, such apparatus may be used to measure gauge pressure regardless of other environmental changes. In a preferred embodiment, the signal optical fibre is secured at or adjacent one end to a fixed location on the apparatus and has its opposite end, or a portion of its length, fastened to the pressure responsive element so that it is under tension, whilst the reference optical fibre is secured at or adjacent both its opposite ends to fixed locations on the apparatus. In order to compensate more fully for physical pertubations other than the measurand, the reference arm is disposed, relatively to the signal arm, in the optimum position for this purpose and to this end, may, for example, also have its distal end, or a part of

the reference fibre, attached to a non-movable location of the pressure responsive element.

The interferometer may be of the Michelson or Mach Zehnder type and have an input and output coupled by coupling means to signal and reference arms which are conveniently constructed from single mode optical fibre. With the Michelson configuration, the distal ends of the signal and reference fibres are reflective so as to reflect light beams propagating in the fibres, and the distal end of the signal fibre is mechanically attached to the pressure responsive element. The coupling means is adapted to mix the reflected beams in the two fibres to produce an interference signal at the output of the interferometer. With the Mach Zehnder configuration, the input and output are disposed at opposite ends of the signal and reference fibres and a portion of the length of the signal fibre is fastened to the pressure responsive element. The output coupling means mixes the beams independently propagated in the signal and reference fibres to produce the interference signal at the output.

In other embodiments of the invention, the interferometer device may comprise a Fabry Perot or Polarimetric configuration, in which event the signal and reference arms, in effect, each comprise an individual interferometer of one of these types. The proximal end of each arm is coupled to an input and output via suitable coupling means, for example, a beam splitting device, which is adapted to launch

light into the arm and recover an interference signal therefrom. The distal end of the signal arm may be mechanically attached to the pressure responsive element.

The apparatus may include a light source for illuminating the interferometer device, for example, a laser light source, and means for detecting and processing the output signal(s) to determine the optical phase difference or shift between light beams propagated in the signal and reference arms, which phase shift is related to a change in the pressure applied to the pressure responsive element. Preferably, the laser light source is coupled to the input of the interferometer device by a single mode optical fibre and the detecting and processing means may also be coupled to the output(s) by optical fibre, so that the pressure sensing head, itself, has a remote installation capability.

The arrangement of the light source and signal detection/processing means may be similar to that described in our International Specification No. WO84/04385 in conjunction with a temperature sensor. Hence, means may be provided for modulating the laser injection current of a laser light source so as to produce a moving interference pattern which is detected at the or each output of the interferometer device by a photodetector and processed to determine the optical phase shift(s) between the light beams propagated in the signal and reference arms. The processing means may be arranged to

compare the laser current modulating signal with the signal at the output of the photodetector to derive a signal corresponding to the optical phase shift.

In order that the present invention may be more readily understood, reference will now be made to the accompanying drawings, in which:-

Figure 1 is a schematic and block circuit diagram of one embodiment of the invention, and

Figure 2 illustrates the signal waveforms occurring at various points in the circuit of Figure 1.

Referring to Figure 1, the apparatus includes a pressure sensing head 1 which comprises a cylindrical housing 2 containing a pressure responsive element 3, in the form of a resilient diaphragm secured across one end of the housing, and an interferometer device 4 arranged to sense movements of the diaphragm 3. The interferometer is housed in a tube 5 which is supported in the housing 2 from a support plate 6 secured to the walls of the housing. As illustrated, the latter may be formed in three parts 2a, 2b, 2c to permit ready assembly of the housing with the diaphragm and interferometer within the housing. Differential fluid pressure is applied to the diaphragm 3 via ports 7 and 8 in opposite ends of the housing and an opening 9 in the support plate 6. For example, one of the ports 7,8 may be connected to a source of pressure to be monitored whilst the other port is connected to atmosphere.

The interferometer 4 comprises optical fibre

signal and reference arms 9,10 disposed juxtaposed one another and formed from single mode optical fibre. Light is launched into the respective optical fibres, and reflected light is recovered therefrom, by a single mode fibre optic directional coupler 11 connected to the proximal ends of the fibres, and the distal ends of the latter may be coated to improve reflectance. Adjacent its proximal end, the signal fibre 9 is rigidly secured to a fixed location 12 on the support tube 5 whilst its distal end is attached to the centre of the pressure sensitive diaphragm 3 at 13 so that the signal fibre is maintained under tension. The reference fibre 10 is rigidly secured at or adjacent both its proximal and distal ends to fixed locations 14,15 on the support tube.

Light from a single frequency semi-conductor diode laser 16 is launched into a single mode optical fibre 17, via an isolator 18 and is supplied to the input 19 of the interferometer at the directional coupler 11 which amplitude divides the light into the signal and reference fibres 9,10. The resulting optical beams propagated in the signal and reference fibres are reflected from the distal ends of the fibres back to the coupler 11 which coherently recombines the light to produce an interference signal at the output 20 of the interferometer, which signal is monitored to recover the optical phase difference between the signals in the two fibres from the intensity of the recombined light signals. In the present embodiment, this is achieved by using a signal processing

technique similar to that described in our aforementioned International specification. The light intensity is conveniently monitored by guiding the interference signal through an optical fibre 21 to a photodetector 22. The light source 16, detector 22 and signal processing electronics may therefore be situated remotely from the pressure sensing head 1.

The signal fibre 9 is maintained under tension such that a change in differential pressure across the pressure responsive diaphragm 3 results in a change in the length of the signal optical fibre. Hence, by detecting and processing the interference signal produced at the output 20 the pressure change may be determined. In one typical example having an Inconel x circular diaphragm 3 of thickness 0.102 mm (0.004") and diameter 71.1 mm (2.800") differential pressure measurements in the range 0 - 100 mbar with a resolution of 10^{-4} mbar have been achieved. As the signal and reference fibres 9,10 are housed in a similar environment, their equal responses to physical perturbations, for example, temperature, other than the pressure measurand, cancel one another out by the process of common mode rejection. The device therefore shows negligible cross sensitivity and, once calibrated, does not normally require recalibration for different applications or changes in the environment in which it is used.

The signal processing system comprises an oscillator or ramp generator 23 for modulating the laser injection current which is supplied by a DC

cell 24 (e.g. a Ni-Cad cell), with a high frequency ramp current. This ramping signal may have a frequency in the range from 100 Hz - 10 kHz, e.g. 5 kHz. A high frequency reference square wave derived from the oscillator 23 via a JK flip-flop 25, which also divides the signal by two, is supplied to one input of the phase comparator 26.

The output from the photodiode detector 22 is connected to one input of a high gain comparator 27 having its other input 27<u>a</u> connected to a reference voltage. The output of the comparator 27 is a square wave and this is fed to one input of a logic AND gate 28 having its output connected, via a JK flip-flop 29, which divides the signal from the AND gate 28 by two, to the second input of the phase comparator 26. The output of the latter is connected to the second input of the AND gate 28 and also to one input of a second logic AND gate 30 having its other input 30<u>a</u> connected to receive pulses from a clock pulse generator, for example, a 1 MHz generator. The signals from the output of the gate 30 are fed, via a timer 31, to a microprocessor 32 for processing and storing.

In Figure 2, r(t) and p(t) show the time variation of the optical intensity at the interferometer output when the laser injection current is ramp-modulated. This output is fed to the high-gain comparator 27 and 'hard-limited' to form a series of pulses c(t). The remaining electronics measure the time $t_1 = (\tau - \tau_D)$ where τ is the time, between the start of the ramp r(t) and the first negative

edge encountered in the photodiode output signal p(t), and τ_D is the time delay. This time, t_1 is directly related to the optical phase shift between the arms 9,10 of the interferometer; t_1 is measured by performing a phase comparison between the square wave, derived from the first negative edge in the photodiode output in each ramp period, and the reference square wave obtained directly from the ramp generator 23. The ramp generator frequency is chosen to be two orders of magnitude higher than the pressure induced fringe drift rate so that relatively simple decision making electronics are used to determine when the fringe pattern corresponds to a new fringe number. By using the 1 MHz clock an accurate determination of the pulse width t_1 is obtained, from which the direction and magnitude of the pressure change is determined. The lower two traces c(t) and d(t) in Figure 2 show the output of the comparator 27 in the upper trace and the input of the microcomputer 32 in the lower trace.

Whilst a particular embodiment has been described, it will be understood that modifications can be made without departing from the scope of the invention as defined by the appended claims. For example, the interferometer 4 may be constructed in a Mach Zehnder configuration instead of the Michelson arrangement illustrated. In this event, the optical fibre signal arm 9 has a portion of its length fastened along the surface of the diaphragm 3 and the input and outputs are at opposite ends of the

signal and reference arms. In other embodiments, the signal and reference arms 9,10 may each be formed as a Fabry Perot or Polarimetric interferometer with the light being launched into and recovered from the proximal ends of the interferometers via associated beam splitting devices. With the Fabry Perot configuration, the light may be supplied to the signal and reference arms via fibre optic leads which are connected to the fibre optic arms by reflective splices. With the Polarimetric configuration, the signal and reference arms are made from birefringent fibre. In either of the latter two embodiments, signal processing systems similar to that illustrated in Figure 1 may be connected to each arm and the outputs from the two systems may be compared to produce a pressure measurement signal which is substantially independent of changes in other environmental conditions in which the pressure sensing head 1 is used.

CLAIMS

1. Optical pressure sensing apparatus characterised by an optical fibre interferometer device (4) arranged to sense the movement of a resilient pressure responsive element (3), whereby an interference signal produced at an output (20) of the interferometer device is responsive to changes in the pressure applied to the pressure responsive element.

2. Apparatus according to claim 1, characterised in that the interferometer device (4) comprises an optical fibre signal arm (9) and an optical fibre reference arm (10), the signal arm being mechanically or optically coupled to the pressure responsive element (3) so that the length of the optical path defined by the signal arm changes relatively to that of the reference arm in response to movement of the pressure responsive element.

3. Apparatus according to claim 2, characterised in that the interferometer device is of the Michelson or Mach Zehnder type and comprises an input (19) and output (20) coupled by coupling means (11) to the signal and reference arms (9,10), which are preferably constructed from single mode optical fibre.

4. Apparatus according to claim 1 or 2, characterised in that the interferometer device (4) comprises a Fabry Perot or Polarimetric configuration in which the signal and reference arms (9,10) each comprise an optical fibre interferometer of one of these configurations, each arm (9,10) being coupled to an input and an output via coupling means which is adapted to launch light into the arm and recover reflected

light therefrom to produce an interference signal at the associated output.

5. Apparatus according to claim 3 or 4, characterised in that the signal arm (9) has its proximal end adjacent the coupling means (11) secured to a fixed location (12) and its distal end (13) attached to the pressure responsive element (3), and in that the reference arm (10) is secured at or adjacent both its proximal and distal ends to fixed locations (14,15) the distal ends of the signal and reference arms being reflective.

6. Apparatus according to any preceding claim, characterised by a light source (16) coupled to the input (19) of the interferometer device via a single mode optical fibre (17).

7. Apparatus according to any preceding claim, characterised by means (22-32) for detecting and processing the output(s) (20) of the interferometer device to determine the optical phase shift between light beams propagated in the signal and reference arms (9,10), which phase shift is responsive to change in the pressure applied to the pressure responsive element (3), said detecting and processing means being coupled to the output(s) (20) by optical fibre (21).

8. Apparatus according to claim 7, characterised by a laser light source (16) for illuminating the interferometer device (4) and means (23) for modulating the laser injection current to produce an interference signal at the or each output (20) in the form of a moving interference pattern.

9. Apparatus according to claim 8, characterised in that the modulating means (23) modulates the bias injection current of the laser with a ramp signal to produce a linearly moving interference pattern at the or each output (20) of the interferometer device.

10. Apparatus according to claim 8 or 9, characterised in that the processing means compares the laser current modulating signal with the signal at the output (20) of the interferometer device to derive a signal corresponding to the optical phase shift.

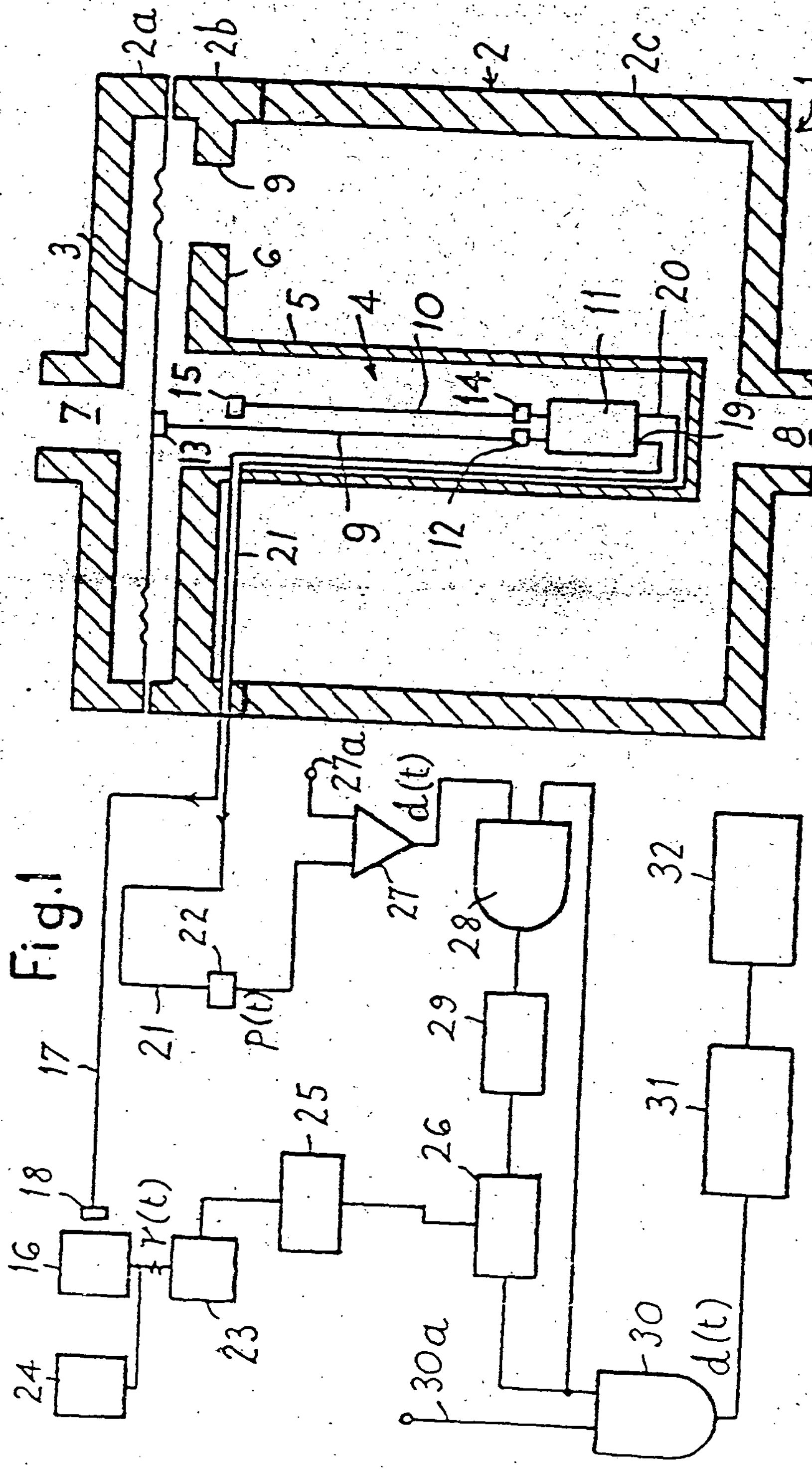
2a
2b
2
2c
1
3
9
6
5
4
10
20
11
7
15
14
13
19
8
9
12
21
27a
d(t)
27
28
22
21
p(t)
17
29
25
26
18
16
r(t)
23
24
30a
30
d(t)
32
31

Fig.1

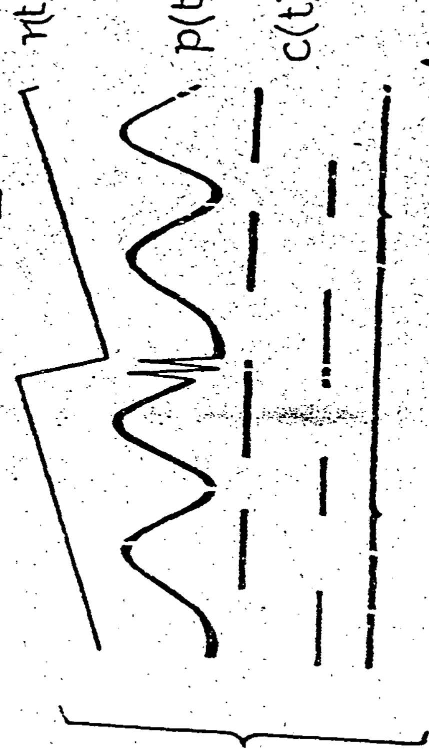
r(t)
p(t)
p(t)
c(t)
d(t)

Fig.2

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 85/00136

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^4: G 01 L 11/00; G 01 L 1/24; G 01 D 5/26

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC^4	G 01 L G 01 D

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	Patent Abstracts of Japan, volume 5, nr. 185, (P-91) (857), 25 November 1981 & JP, A, 56112608 --	1-3
X	DE, A, 3031961 (LICENTIA PATENT-VERWALTUNGS GmbH) 11 March 1982, see figures 1-3; introduction; page 4, line 33 - page 7, line 23; page 9, lines 4-17 --	1-5,7
X	EP, A, 0021199 (TOKYO SHIBAURA DENKI, K.K.) 7 January 1981, see figures 2,3,12; page 14, line 19 - page 17, line 30 --	1-10
A	EP, A, 0013974 (ROCKWELL INTERNATIONAL CORP.) 6 August 1980, see figures 1,3,4,5; page 5, line 1 - page 6, line 9; page 10, line 1 - page 14, line 2 --	1-3,6,7

* Special categories of cited documents: [10]

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
27th June 1985	26 JUIL. 1985
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	f.o G.L.M. Kruydenberg

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
A	Elektronik, volume 31, nr. 12, June 1982; (Müchen, DE) J. HESSE; W. SOHLER:"Faseroptische Sensoren", pages 89-92 see page 89, paragraphs 2,3; (3.1,3.4); figures 1,3,4,5	1-4

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/GB 85/00136 (SA 9143)

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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
DE-A- 3031961	11/03/82	None		
EP-A- 0021199	07/01/81	JP-A-	55164995	23/12/80
		US-A-	4334781	15/06/82
		JP-A-	56002095	10/01/81
EP-A- 0013974	06/08/80	JP-A-	55099018	28/07/80
		US-A-	4329058	11/05/82

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